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LARGE-ARRAY SIGNAL AND NOISE ANALYSIS

Special Scientific Report No. 8

SHORT-PERIOD SIGNAL WAVEFORM SIMILARITY AT LASA

Prepared by

Terence W. Harley Thomas D. Laney
Frank H. Binder, Program Manager

TEXAS INSTRUMENTS INCORPORATED
Science Services Division
P.O. Box 5621
Dallas, Texas 75222

Contract No. AF 33(657)-16678

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C. 20333

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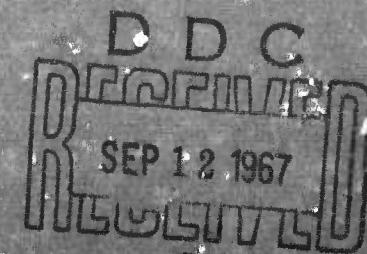
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ARPA Order No. 599
AFTAC Project No. VT/6707

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ABSTRACT

Similarity of signal waveform across the Large Aperture Seismic Array (LASA) was studied. The analysis technique depended on differences in waveform shape but not on amplitude differences.

The waveform was found to be very similar both within subarrays and, except for a few cases, between subarrays. Thus, 1-pt (amplitude) equalization usually is sufficient when processing LASA data both on the subarray and large-array levels.



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SECTION I

INTRODUCTION

The purpose of this study was to measure the similarity of signal waveforms across LASA both within subarrays and between subarrays. The following three types of signal similarity were analyzed:

- (1) Single seismometers within a subarray. All seismometers at each of two subarrays (F3 and F4) were used for this study.
- (2) Single seismometers between subarrays. The center seismometers from all subarrays were used for this study.
- (3) Subarray outputs. The time-shifted sums from all subarrays were used for this study.

The five events used for analyses (1) and (2) are listed in Table 1; the 20 events used for analysis (3) are listed in Table 2. Two events are common to both tables. For analyses (1) and (2), the events were chosen from a suite which had been demultiplexed under another task of the LASA contract. For analysis (3), the events were chosen from the suite used to study the relative capabilities of large and small seismic arrays * for event identification.

All events were resampled to a 0.1 -sec rate and bandpass filtered with a zero-phase 0.8 to 2.8 cps digital filter (Figure 1) to reduce the low-frequency ambient noise. Only events with a large signal-to-noise ratio were used.

* Texas Instruments Incorporated, 1967: Large Array Signal and Noise Analysis, A study of the Relative Capability of Large and Small Seismic Arrays for Event Identification, Spec. Rpt. No. 1, Contract AF33(657)-16678, 20 April.



Table 1

DATA USED FOR SINGLE SEISMOMETER PROCESSING

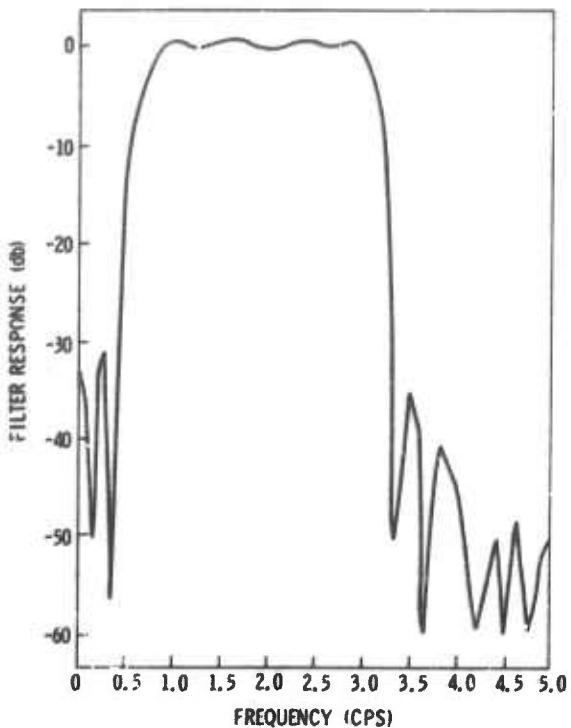
Location	Latitude (°)	Longitude (°)	Date	Origin Time (GMT)	Depth (km)	Magnitude	Epicentral Distance (°)	Azimuth (°)
Andreanof Islands*	51.2N	178.1W	1-5-66	7:01:58.1	33	5.0	45.9	303.6
Colombia*	6.8N	73.1W	1-6-66	4:19:59.3	168	5.3	49.1	134.0
Mexico	15.9N	93.6W	2-6-66	4:12:26.7	92	5.2	32.1	156.7
W. Pakistan	29.8N	69.7E	2-7-66	4:26:13.9	33	6.0	103.8	3.6
Panama	5.0N	82.4W	4-15-66	6:42:59.7	33	4.8	46.1	146.0

* Also used for subarray output processing

Table 2
DATA USED FOR SUBARRAY OUTPUT PROCESSING

Event No.	Location	Latitude (°)	Longitude (°)	Date	Origin Time (GMT)	Depth (km)	Magnitude	Epicentral Distance (°)	Azimuth (°)
2	Fiji Islands	17.75	178.3W	12-9-65	13:25:40.7	650	5.1	91.1	245.1
9	Kurile Islands	48.4N	154.7E	11-21-65	6:10:56.3	33	4.7	61.9	311.7
9	Colombia *	6.8N	73.1W	1-6-66	4:19:59.3	168	5.3	49.1	134.0
12	Peru	17.85	59.6W	11-10-65	1:47:22.8	140	4.3	72.2	143.0
17	Andreanof Islands *	51.4N	179.7W	11-23-65	2:17:49.4	48	5.6	46.5	142.5
18	E. Kamchatka	55.2N	163.0E	11-25-65	3:35:11.7	23	5.0	54.2	304.1
21	Kurile Islands	50.5N	155.3E	12-11-65	12:16:59.9	110	4.9	60.7	313.6
24	Andreanof Islands	51.2N	178.1W	1-5-66	7:01:58.1	33	5.0	45.9	303.6
25	E. Kamchatka	52.6N	160.0E	1-7-66	7:45:27.3	92	5.1	57.1	313.6
27	Tadzhik	39.3N	73.1E	1-28-66	8:52:02.2	20	5.4	94.4	0.5
29	W. Pakistan	29.8N	69.7E	2-7-66	4:26:13.9	33	6.0	103.8	3.6
36	Aleutian Islands	52.8N	170.3E	6-12-66	6:49:09.0	33	4.5	51.4	309.5
40	Andreanof Islands	52.4N	179.10W	11-23-65	6:16:26.0	33	4.3	46.8	304.5
101	Algeria	24.0N	5.1E	12-1-65	10:29:58.0	0	5.0	86.3	58.6
102	E. Kasakh	49.8N	78.1E	11-21-65	4:57:57.9	0	5.8	83.8	357.2
104	Rat Islands	51.4N	170.2E	10-29-65	21:00:00.1	0	6.1	47.1	304.6
105	E. Kasakh	49.8N	78.1E	2-13-66	4:47:57.7	0	6.3	83.6	357.2
106	E. Kasakh	49.7N	77.9E	4-21-66	3:57:58.0	0	5.5	83.8	357.2
108	E. Kasakh	49.9N	78.0E	6-29-66	6:57:58.1	0	5.7	83.7	357.3
112	E. Kasakh	—	—	3-20-66	—	—	—	~ 83.8	~ 357.2

* Also used for single seismometer processing



**Figure 1. Amplitude Response of 3.7-sec
Zero-Phase Bandpass Filter:
100 msec Sample Rate; 0.8 to
2.8 cps Passband**



SECTION II

ANALYSIS TECHNIQUE

Waveform similarity was measured by computing correlation coefficients between given traces and a reference trace. For single seismometers within a subarray, the reference trace used was the subarray time-shift-and-sum. The time-shift-and-sum of the single seismometers involved was the reference trace used for single seismometers between subarrays. For subarray outputs, the reference trace used was the LASA time-shift-and-sum. In each case, the reference trace was thus the appropriate average of the input traces.

Using the appropriate average as a reference rather than some arbitrary individual trace was preferable because, in cases where that individual trace had a significantly different waveform than the other traces, a low set of correlation coefficients resulted. By using the average trace as a reference, only the correlation coefficient associated with that trace was low. The correlation coefficient ρ was defined as

$$\rho = \frac{\varphi_{ir}(\tau)}{\sqrt{\varphi_{ii}(0)} \sqrt{\varphi_{rr}(0)}}$$

where

$\varphi_{ir}(\tau)$ is the maximum lag of the crosscorrelation between the individual and reference traces

$\varphi_{ii}(0), \varphi_{rr}(0)$ is the zero-lag autocorrelations of the individual and reference traces



The "full-house" correlation technique was used in the computations. That is, the gates were chosen in such a way that $\rho = 1$ if the waveforms are identical except for being displaced by a lag τ .

The gate lengths used to compute the correlations were visually chosen to include the main signal arrival. When the signal had fairly long duration, several gates were usually selected.

The correlation coefficient was chosen as the analysis tool because it measured differences in waveform, was a relatively inexpensive method of analysis, and did not depend on gain differences between channels. However, the effect of a linear filter was reflected in the correlation coefficient (as contrasted with the 2-channel coherence technique). That is, let

$$i(t) = r(s) * h(s)$$

where

$i(t)$ is an individual trace

$r(s)$ is the reference trace

$h(s)$ is a linear fil

* stands for convolution

Then,

$$\begin{aligned}\varphi_{ir}(\tau) &= r(s) \Phi [r(s) * h(s)] \\ &= \varphi_{rr}(t) * h(t)\end{aligned}$$

$$\begin{aligned}\varphi_{ii}(\tau) &= [r(s) * h(s)] \Phi [r(s) * h(s)] \\ &= \varphi_{rr}(t) * \varphi_{hh}(t)\end{aligned}$$

$$\varphi_{ii}(0) = \varphi_{rr}(\tau) * \varphi_{hh}(\tau) \Big|_{\tau=0}$$

where Φ stands for "correlated with."



Therefore,

$$\rho = \frac{\varphi_{rr}(t) * h(t)}{\sqrt{\varphi_{rr}(0)} \sqrt{\varphi_{rr}(t) * \varphi_{hh}(t)} \Big|_{\tau=0}}$$

and, unless $h(s)$ is a 1-pt filter, $\rho \neq 1$.

The mean and variance of the set of correlation coefficients were computed for each event, and measures of both signal degradation and signal-to-noise ratio were obtained. Signal degradation "L" was obtained by choosing the largest peak-to-peak amplitude in the first few cycles and computing

$$L = 20 \log_{10} \frac{A_r}{\frac{1}{N} \sum_{i=1}^N A_i}$$

where

L is the signal degradation in db

A_r is the peak-to-peak amplitude
on the reference trace

A_i is the peak-to-peak amplitude on an
individual trace

N is the number of individual traces

Care was taken to insure that the same cycle was measured on each trace.



The signal-to-noise ratio was defined as

$$\frac{S}{N} = \frac{A_{\max}}{N_{\text{rms}}}$$

where

A_{\max} is the maximum zero-to-peak amplitude
in the first few cycles

N_{rms} is the rms level of the noise immediately
preceding the signal

Finally, an attempt was made to relate the means and/or variances of the correlation coefficients to both signal degradation and signal-to-noise ratio.



SECTION III

PRESENTATION OF DATA

A. INTRASUBARRAY

To analyze the similarity of single-seismometer outputs within a subarray, the five events listed in Table 1 were used.

Subarrays F3 and F4 were chosen because they usually had larger signal-to-noise ratios than other subarrays. Figure 2 shows the reference trace (subarray time-shift-and-sum) for each event and the gates used in computing the correlation coefficients.

Table 3 gives the correlation coefficients of each seismometer for each event. It can be seen that most of the coefficients were close to 1.0. Excluding subarray F3 for the Andreanof Islands event, only seven coefficients were less than 0.9 and only one (seismometer 45, subarray F3, Colombia event) was less than 0.80. Subarray F3 was anomalous for the Andreanof Islands event.

Figure 2 shows that the large-amplitude arrival for subarray F3 was delayed. It was the first arrival for the other subarrays. Because of this delay, the correlation coefficient for F3 was computed over a gate with a relatively small signal-to-noise ratio, adversely affecting the correlation coefficient. A second set of coefficients computed over a gate which contained the large arrival was considerably higher. Figure 3 shows the Panama event as recorded at both subarrays and is typical of the waveform duplication observed at the subarray level.

The maximum variations in amplitude (i. e., the ratio of the largest to smallest amplitude) across a subarray for each event are given in Table 4. Variations ranged up to 7 db, showing a need for

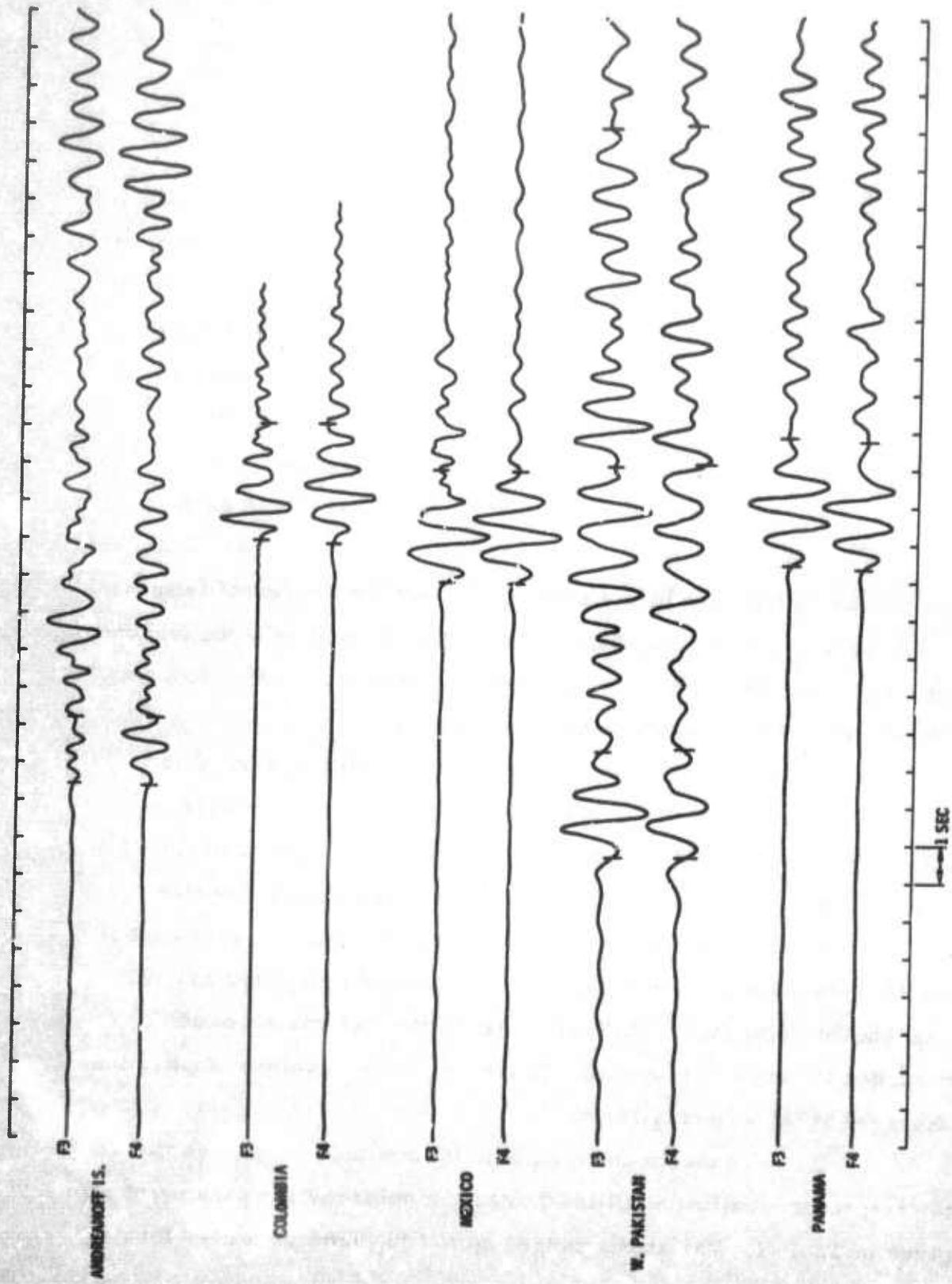


Figure 2. Reference Traces for Events Used for Single Seismometer Processing Within Subarrays



Table 3
CORRELATION COEFFICIENTS WITHIN SUBARRAYS
F3

Seismometer	Andreanof Islands	Colombia	Mexico	Pakistan	Panama
10	0.976	0.977	0.976	0.977	0.974
21	0.979	0.904	0.993	0.945	0.997
41	0.885	0.978	0.986	0.994	0.963
61	0.855	0.976	0.980	0.972	0.964
81	0.868	0.866	0.958	0.958	0.980
22	0.945	0.978	0.982	0.998	0.944
32	0.853	0.972	0.993	0.943	0.987
52	0.922	0.976	0.948	0.957	0.994
72	0.937	0.949	0.982	0.982	0.980
23	0.914	0.977	0.978	0.994	0.984
43	0.947	0.955	0.964	0.998	0.951
63	0.859	0.893	0.994	0.992	0.988
83	0.868	0.903	0.963	0.987	0.997
24	0.969	0.990	0.995	0.978	0.995
34	0.921	0.931	0.988	0.997	0.992
54	0.817	0.971	0.993	0.946	0.983
74	0.747	0.885	0.984	0.949	0.980
25	0.978	0.956	0.964	0.954	0.968
45	0.856	0.696	0.985	0.976	0.953
65	0.887	0.271	0.973	0.959	0.975
85	0.878	0.921	0.984	0.989	0.964
26	0.972	0.940	0.991	0.962	0.992
36	0.865	0.978	0.986	0.952	0.991
56	0.926	0.893	0.994	0.989	0.982
76	0.804	0.913	0.940	0.951	0.947

Table 3 (Contd)

F4

Seismometer	Andreanof Islands	Colombia	Mexico	Pakistan	Panama
10	0.958	0.945	0.980	0.994	0.994
21	0.940	0.911	0.957	0.980	0.955
31	0.956	0.974	0.972	0.992	0.954
51	0.986	0.967	0.989	0.958	0.990
71	0.970	0.947	0.961	0.937	0.980
22	0.929	0.937	0.968	0.991	0.995
42	0.948	0.988	0.990	0.980	0.976
62	0.962	0.954	0.944	0.989	0.997
82	0.992	0.971	0.981	0.995	0.989
23	0.933	0.994	0.992	0.994	0.973
33	0.994	0.970	0.988	0.997	0.956
53	0.983	0.972	0.955	0.995	0.996
73	0.965	0.947	0.951	0.982	0.977
24	0.954	0.988	0.999	0.993	0.992
44	0.988	0.948	0.996	0.987	0.989
64	0.974	0.900	0.987	0.957	0.991
84	0.974	0.925	0.991	0.969	0.991
25	0.988	0.967	0.990	0.997	0.984
35	0.992	0.933	0.998	0.993	0.998
55	0.988	0.932	0.987	0.963	0.993
75	0.976	0.908	0.973	0.990	0.988
26	0.994	0.929	0.974	0.991	0.988
46	0.956	0.942	0.994	0.995	0.994
66	0.945	0.966	0.961	0.985	0.969
85	0.988	0.874	0.970	0.973	0.989

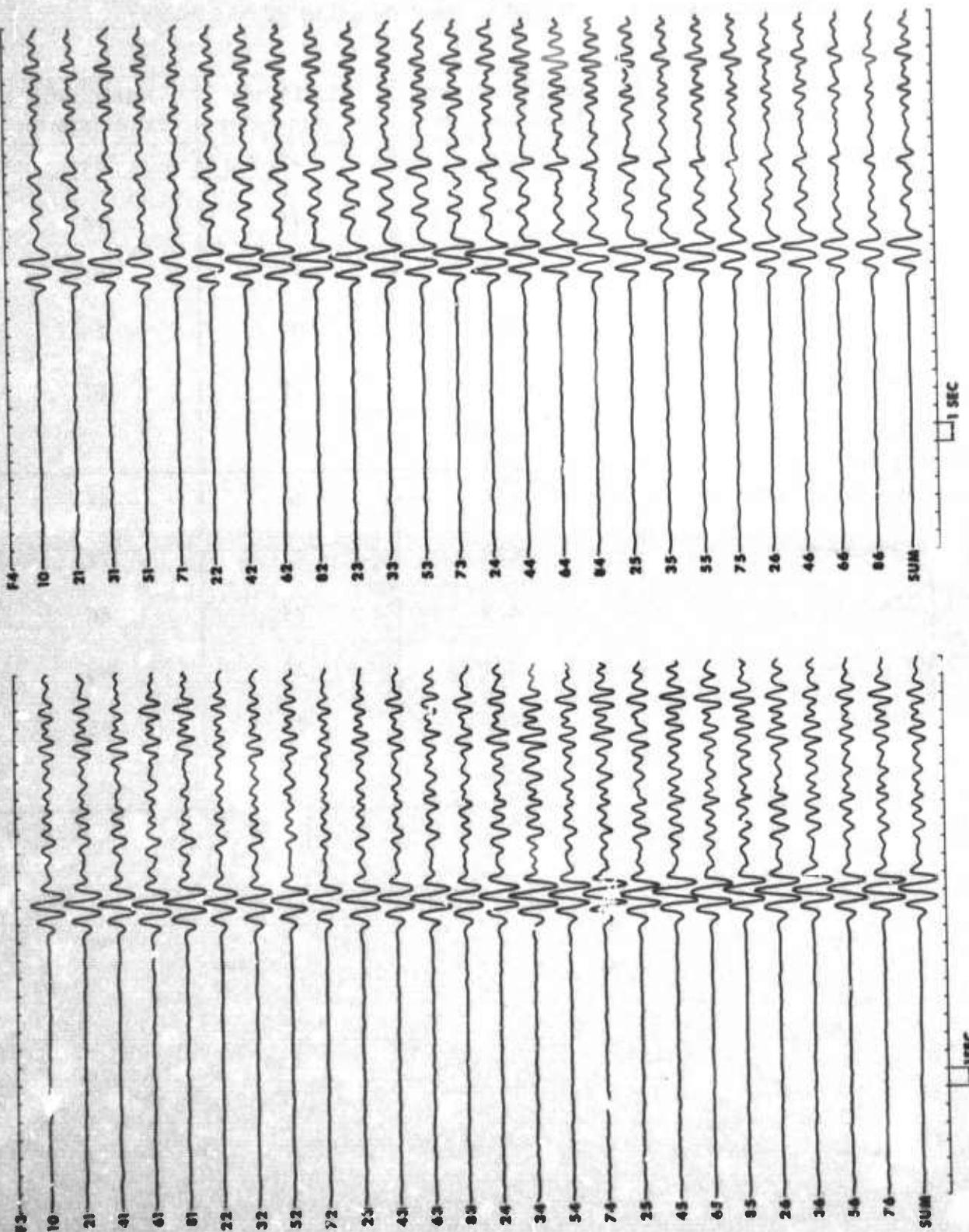


Figure 3. Panama Event as Recorded at Subarrays F3 and F4



Table 4
MAXIMUM AMPLITUDE VARIATION ACROSS SUBARRAYS

	Event	Maximum Amp Variation (db)	Maximum Seismometer	Minimum Seismometer
F3	Andreanof Islands	7.0	61	54
	Colombia	4.2	76	72
	Mexico	1.7	81	72
	W. Pakistan	2.6	34	76
	Panama	4.3	26	72
	Average	4.0		
F4	Andreanof Islands	6.4	24	86
	Colombia	6.9	73	71
	Mexico	2.9	84	86
	W. Pakistan	3.4	24	26
	Panama	4.7	24	86
	Average	4.9		



amplitude equalization at the subarray level. Note that seismometers with the largest and smallest amplitudes were different for different events — possibly due to either statistical seismometer-gain fluctuations or a "tuning" of individual seismometers to epicentral regions which was probably caused by nonhomogenous seismometer-ground coupling.

Table 5 lists the correlation coefficients for the Pakistan event (Figure 4) for several gate lengths and shows that they remained high even for long gates. This indicates that scattered energy is not a problem for this event. Similar results for other events indicate that, in general, scattered energy is not a problem at the LASA site.

Table 6 lists the means and variances of the correlation coefficients, the signal degradations, and the signal-to-noise ratios of the subarray sums for the five events.

Subarray-F4 signals seem to have more similarity than those in F3, as indicated by their higher means, lower variances, and smaller degradation values. Those events with the larger coefficient means had less signal degradation (as would be expected), although all events had less than 1-db degradation. With the exception of the Andreanof event on F3, all events had sufficiently large signal-to-noise ratios to prevent the ambient noise from affecting the correlation-coefficient values.

B. SINGLE SEISMOMETERS BETWEEN SUBARRAYS

To analyze the similarity of single seismometer outputs between subarrays, the same five events listed in Table I were used.



Table 5
CORRELATION COEFFICIENTS ON F3 AND F4
FOR SEVERAL GATES -- PAKISTAN EVENT

F3	29 Points	105 Points	195 Points	F4	29 Points	105 Points	195 Points
10	0.971	0.971	0.958	10	0.994	0.982	0.968
21	0.939	0.944	0.928	21	0.981	0.972	0.950
41	0.989	0.985	0.961	31	0.985	0.962	0.959
61	0.962	0.961	0.917	51	0.932	0.909	0.872
81	0.953	0.910	0.881	71	0.883	0.862	0.817
22	0.994	0.990	0.974	22	0.990	0.972	0.971
32	0.939	0.933	0.921	42	0.976	0.953	0.937
52	0.955	0.923	0.924	62	0.985	0.965	0.928
72	0.979	0.959	0.933	82	0.987	0.918	0.892
23	0.989	0.981	0.969	23	0.992	0.970	0.971
43	0.996	0.962	0.947	33	0.991	0.969	0.958
63	0.989	0.946	0.917	53	0.994	0.947	0.920
83	0.986	0.929	0.867	73	0.975	0.911	0.856
24	0.975	0.976	0.967	24	0.992	0.978	0.974
34	0.990	0.977	0.959	44	0.982	0.960	0.951
54	0.944	0.925	0.880	64	0.957	0.928	0.898
74	0.939	0.904	0.861	84	0.949	0.914	0.864
25	0.949	0.933	0.913	25	0.992	0.961	0.954
45	0.970	0.941	0.934	35	0.992	0.968	0.972
65	0.942	0.956	0.927	55	0.966	0.948	0.923
85	0.981	0.947	0.928	75	0.981	0.942	0.928
26	0.957	0.946	0.942	26	0.988	0.964	0.970
36	0.943	0.928	0.917	46	0.990	0.930	0.934
56	0.982	0.961	0.914	66	0.980	0.886	0.870
76	0.932	0.916	0.848	86	0.959	0.827	0.793
Mean	0.966	0.948	0.924	Mean	0.976	0.940	0.921
Variance	0.0004	0.0006	0.0011	Variance	0.0006	0.0014	0.0025

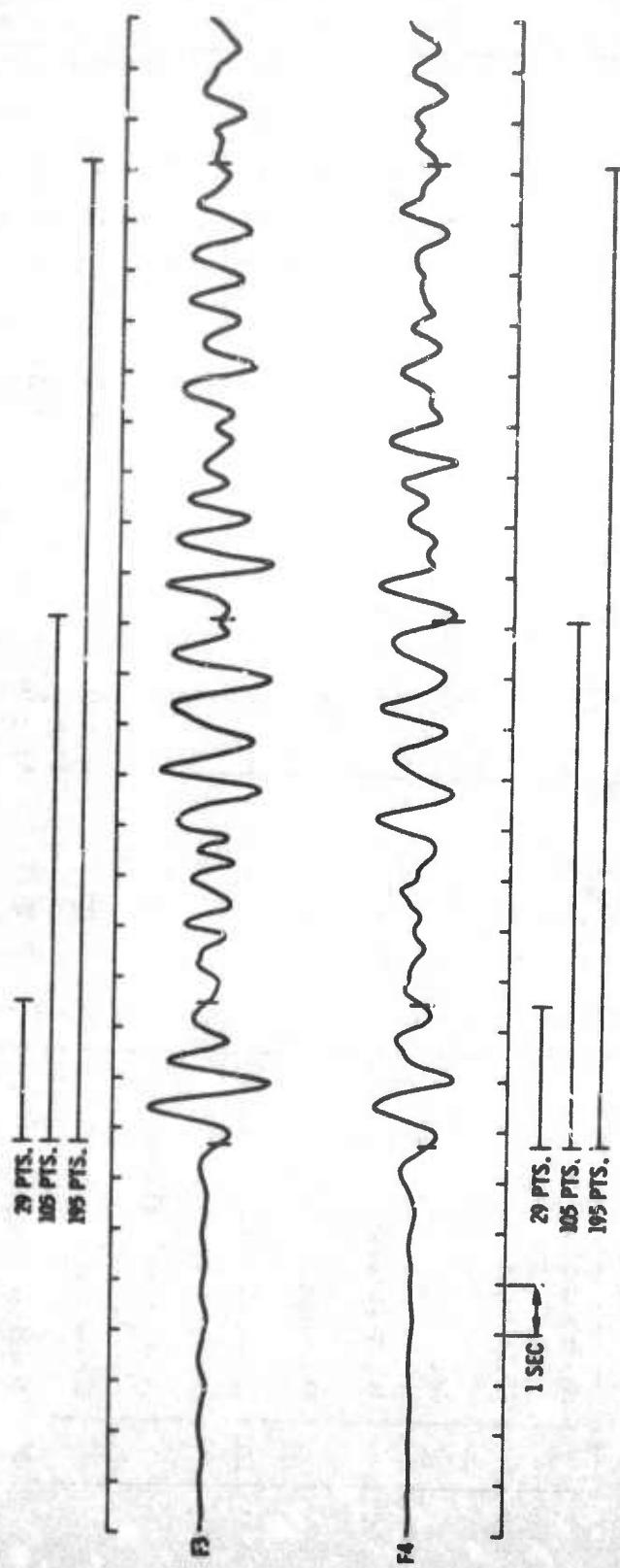


Figure 4. Pakistan Event Illustrating Different Gate Lengths

Table 6

RESULTS FOR SINGLE SEISMOMETERS WITHIN SUBARRAYS

Event	Correlation Coefficient		Signal Degradation (db)	S/N on Reference Trace
	Average	Variance		
Andreanof Islands	0.897	0.0035	0.947	48
	0.941	0.0015	0.901	314
	0.979	0.0002	0.127	141
	0.972	0.0004	0.101	112
	0.977	0.0003	0.364	104
Mexico				
	0.969	0.0004	0.243	79
	0.948	0.0008	0.627	216
	0.978	0.0003	0.044	402
	0.983	0.0002	0.064	63
W. Pakistan				
	0.984	0.0002	0.146	61
Panama				



The center seismometers from all subarrays were chosen, with the time-shift-and-sum used as the reference trace. Figure 5 shows the reference trace for each event and the gates used in computing the correlation coefficients.

Table 7 gives the correlation coefficient for each seismometer for each event. Note that the coefficients were generally large (greater than 0.8), although they were smaller on the average than the intrasubarray values. However, a few seismometers had very low values (e.g., the D2 and the E1 seismometers for the Colombia event); the significance of these low values is discussed in subsection C.

Figure 6 shows the Mexico event as recorded by the 21 center seismometers and indicates that the waveform duplication of single seismometers across LASA was quite good. Maximum variation in amplitude across LASA naturally was much larger than across a subarray (up to 18 db as compared to 7 db for the subarrays). Again, amplitude equalization was necessary (and, in most cases, probably sufficient).

Table 8 lists the correlation-coefficient means and variances, the signal degradation, and the signal-to-noise ratios on the reference traces for the five events. Means were about 0.08 lower than intra-array means, and variances were slightly higher. Again, events with larger coefficient means had less signal degradation.

C. SUBARRAY OUTPUTS

The twenty events listed in Table 2 were used to analyze the similarity of subarray outputs. Figure 7 shows the LASA sum for each event and the gates used in computing the correlation coefficients.

Table 9 lists the correlation coefficients for each subarray output for each event. Figure 8 shows the location of the events on a polar plot centered at LASA. The coefficients were generally large (greater than 0.8), although smaller on the average than the intrasubarray values.

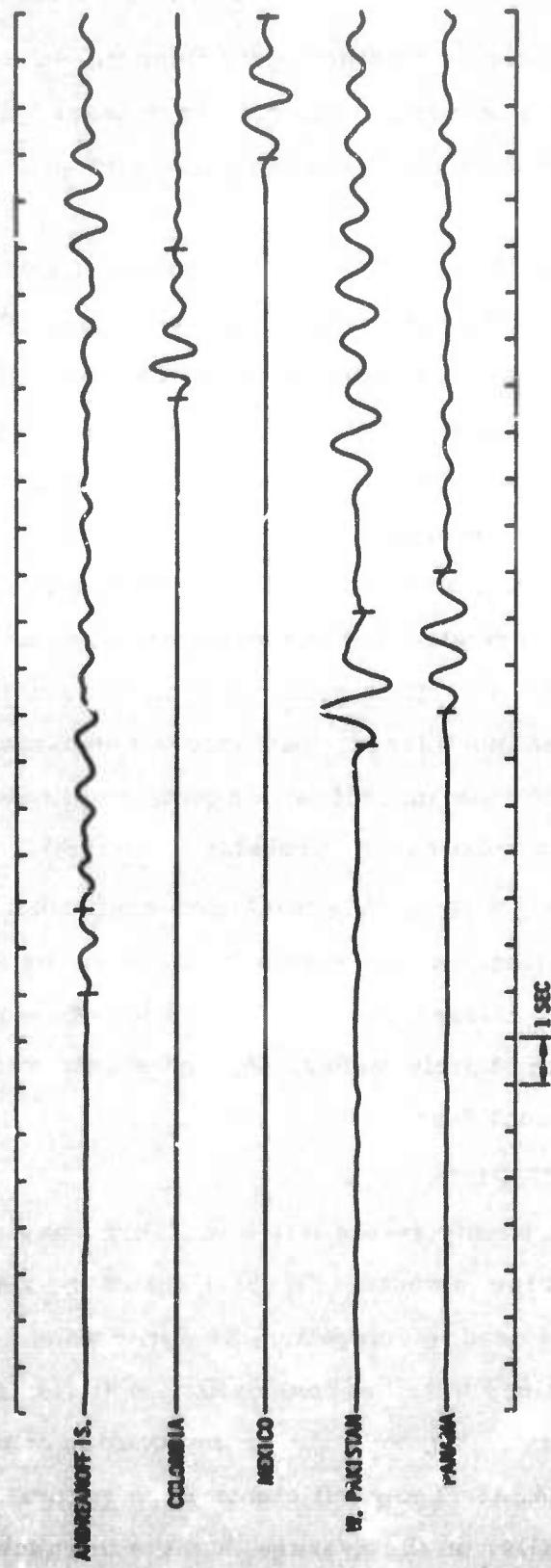


Figure 5. Reference Traces for Events Used for Single Seismometer Processing Between Subarrays



Table 7

CORRELATION COEFFICIENT FOR
SINGLE SEISMOMETERS BETWEEN SUBARRAYS

	Aleutian	Colombia	Mexico	Pakistan	Panama
B1	0.975	0.855	0.771	0.934	0.858
F3	0.929	0.783	0.980	0.876	0.938
F4	0.776	0.786	0.908	0.971	0.967
A0	0.878	0.798	0.923	0.948	0.766
B3	0.919	0.877	0.899	0.964	0.943
C4	0.901	0.811	0.901	0.857	0.964
B4	0.860	0.964	0.910	--	0.982
C1	0.979	0.936	0.925	0.957	0.994
C2	0.945	0.939	0.643	0.736	0.941
B2	0.944	0.828	0.933	0.941	0.908
C3	0.938	0.875	0.970	0.953	0.773
D3	0.933	0.862	0.935	0.885	0.920
D4	0.861	0.760	0.927	0.766	0.926
D1	0.975	0.844	0.916	0.929	0.973
D2	0.983	0.338	0.932	0.948	0.960
E3	0.850	0.875	0.919	0.902	0.855
E4	0.970	0.760	0.931	0.877	0.974
E1	0.933	0.421	0.953	0.801	0.971
F1	0.926	0.756	0.925	0.811	0.944
E2	0.929	0.878	0.551	0.877	0.981
F2	0.836	0.941	0.941	0.847	0.926

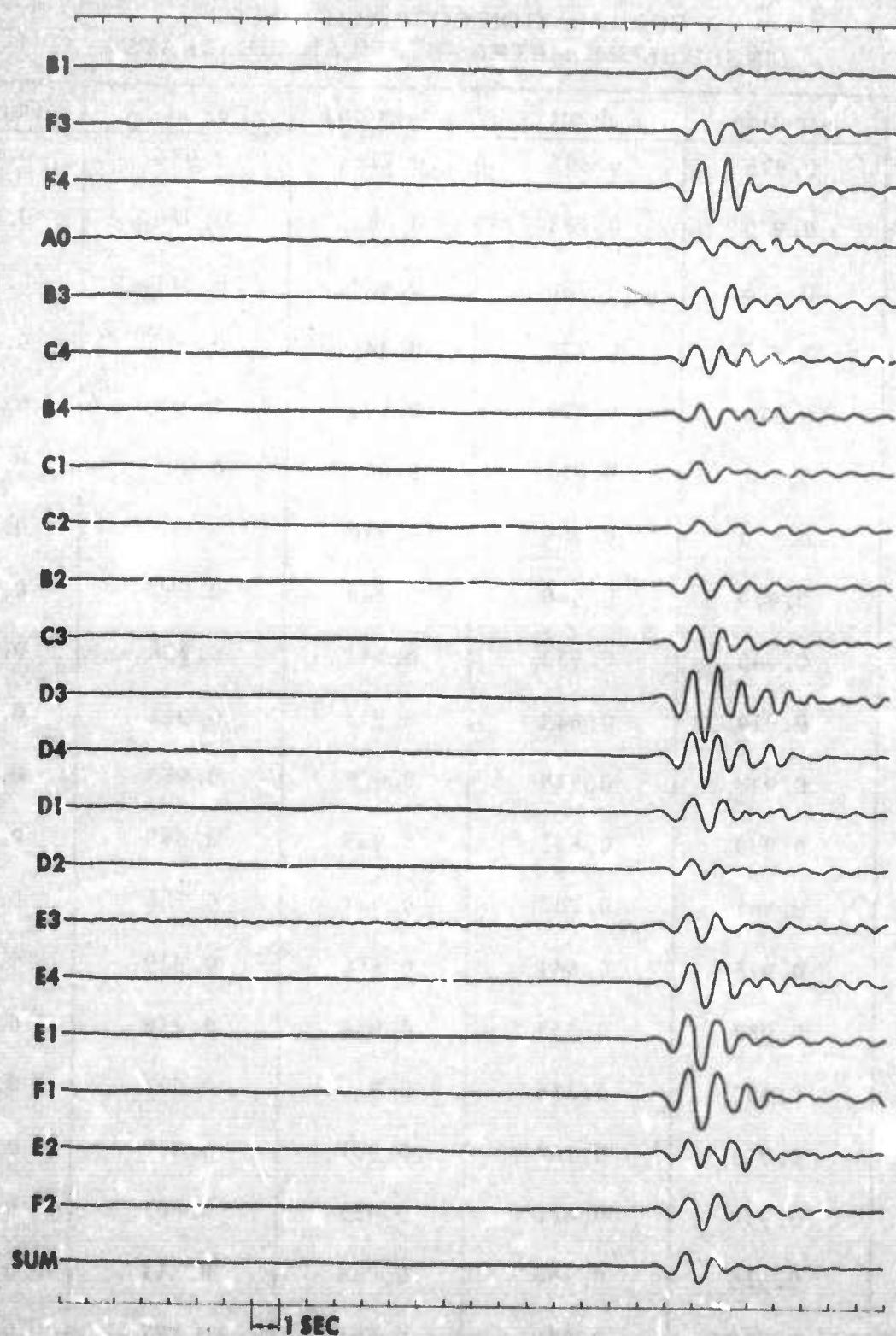


Figure 6. Mexico Event As Recorded by the Center
Seismometers of Each Subarray



Table 8

RESULTS FOR SINGLE SEISMOMETER PROCESSING BETWEEN SUBARRAYS

Event Location	Correlation Coefficient		Signal Degradation (db)	S/N on Reference Trace
	Mean	Variance		
Andreanof Islands	0.917	0.0029	1.35	145
Colombia	0.804	0.0229	1.609	318
Mexico	0.890	0.0107	0.902	303
Pakistan	0.839	0.0045	0.455	99
Panama	0.927	0.0039	0.477	123



EVENT
NUMBER

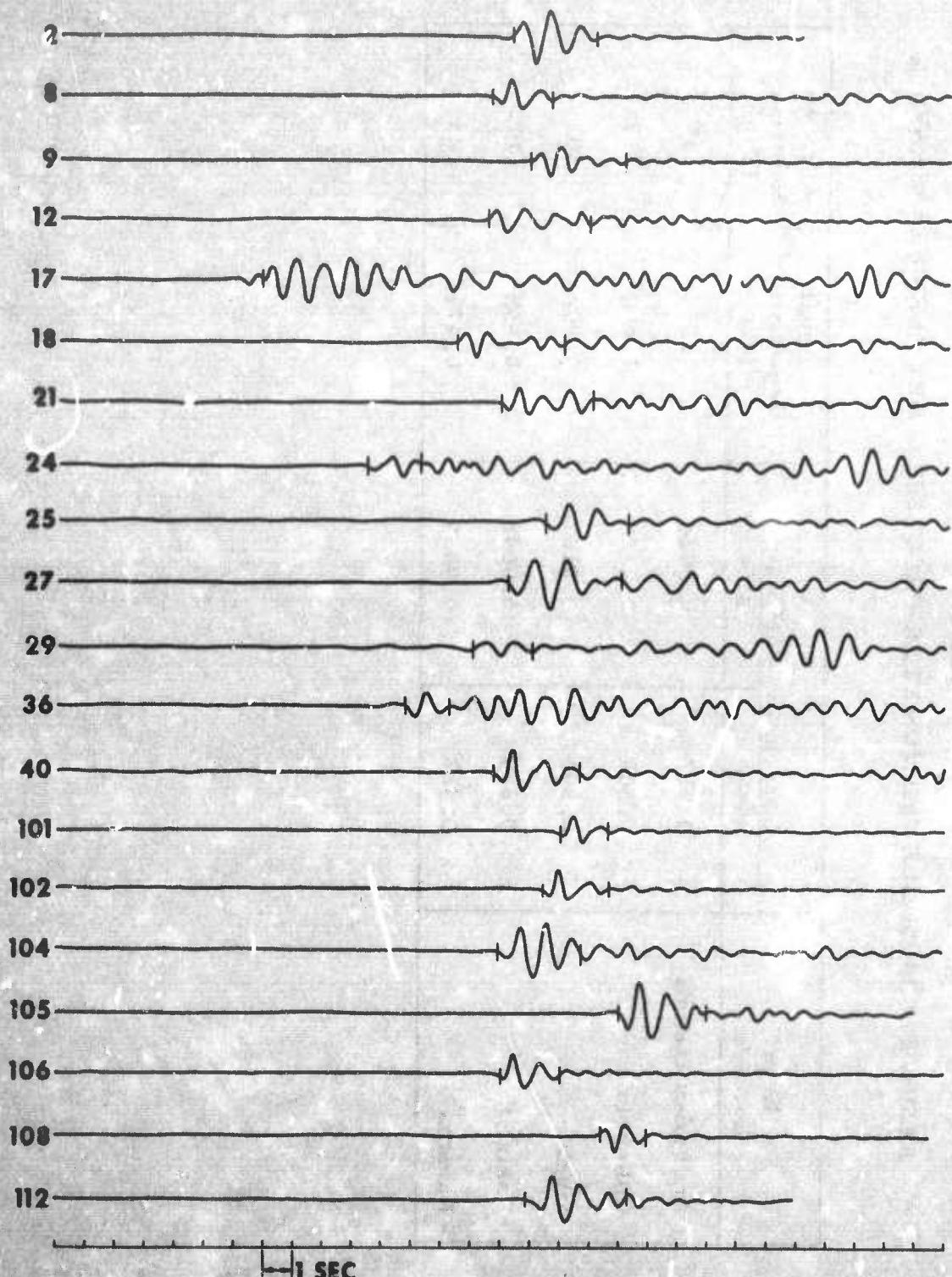


Figure 7. Reference Traces for Events Used
for Subarray Output Processing

Table 9

CORRELATION COEFFICIENTS FOR SUBARRAY OUTPUTS

Row	2	101	12	9	24	17	40	104	36	16	25	21	6	105	100	112	102	106	27	29	
Subarray	F1A Islands (22 pico)	A1B Islands (16 pico)	B1A Islands (16 pico)	C1A Columbian Islands (32 pico)	D1A Andean Islands (16 pico)	E1A Islands (16 pico)	F1A Islands (16 pico)	G1A Islands (16 pico)	H1A Islands (16 pico)	I1A Aluvian Islands (28 pico)	J1A Islands (15 pico)	K1A Islands (28 pico)	L1A Islands (15 pico)	M1A Islands (15 pico)	N1A Islands (15 pico)	O1A Islands (15 pico)	P1A Islands (15 pico)	Q1A Islands (15 pico)	R1A Islands (15 pico)	S1A Islands (15 pico)	T1A Islands (15 pico)
A0	0.977	0.761	0.732	0.764	0.924	0.914	0.770	0.975	0.927	0.939	0.934	0.928	0.941	0.619	0.760	0.677	0.713	0.747	0.579	0.944	
B1	0.941	0.924	0.871	0.849	0.968	0.762	0.943		0.968	0.527	0.943	0.738	0.797	0.931	0.789	0.946	0.765	0.907	0.997	0.948	
B2	0.984	0.939	0.405	0.803	0.914	0.941	0.895		0.895	0.913	0.957	0.950	0.960	0.961	0.972	0.974	0.961	0.960	0.977	0.916	
B3	0.977	0.964	0.871	0.944	0.916	0.929	0.922	0.940	0.946	0.946	0.940	0.940	0.940	0.940	0.974	0.974	0.670	0.387	0.620	0.487	0.480
B4	0.947	0.920	0.849	0.929	0.897	0.842	0.878	0.941	0.956	0.922	0.964	0.941	0.947	0.959	0.919	0.939	0.926	0.969	0.923	0.970	
C1	0.968	0.954	0.859	0.859	0.912	0.903	0.915		0.962	0.949	0.931	0.905	0.945	0.960	0.957	0.959	0.963	0.966	0.976	0.943	
C2	0.947	0.937	0.951	0.895	0.900	0.925	0.870		0.928	0.751	0.854	0.956	0.922	0.910	0.953	0.923	0.925	0.973	0.944	0.972	
C3	0.908	0.367	0.844	0.937	0.936	0.946	0.845	0.960	0.974	0.910	0.922	0.889	0.766	0.871	0.952	0.897	0.943	0.945	0.995	0.979	
C6	0.912	0.845	0.875	0.825	0.926	0.891	0.925	0.927	0.916	0.929	0.983	0.941	0.975	0.775	0.962	0.951	0.924	0.910	0.964	0.943	
D1	0.945	0.797	0.958	0.537	0.953	0.888	0.883		0.899	0.915	0.782	0.744	0.898	0.591	0.316	0.579	0.466	0.348	0.946	0.946	
D2	0.939	0.859	0.923	0.481	0.903	0.935	0.918	0.919	0.956	0.949	0.943	0.900	0.945	0.934	0.916	0.946	0.946	0.946	0.946	0.933	
D3	0.941	0.477	0.863	0.976	0.887	0.942	0.931	0.974	0.963	0.776	0.997	0.955	0.948	0.929	0.942	0.972	0.575	0.976	0.938	0.941	
D4	0.943	0.969	0.871	0.722	0.855	0.776	0.719	0.913	0.920	0.915	0.984	0.979	0.964	0.895	0.760	0.938	0.940	0.940	0.933	0.946	
E1	0.964	0.756	0.866	0.289	0.881	0.952	0.892		0.931	0.842	0.927	0.654	0.680	0.944	0.946	0.962	0.750	0.927	0.913	0.750	
E2	0.961	0.570	0.912	0.827	0.977	0.938	0.925	0.963	0.900	0.780	0.922	0.871	0.828	0.770	0.796		0.812	0.861	0.902	0.867	
E3	0.142	0.879	0.651	0.900	0.766	0.907	0.760	0.926	0.954	0.750	0.958	0.925	0.932	0.951	0.946	0.948	0.938	0.956	0.937		
E4	0.960	0.820	0.895	0.695	0.938	0.936	0.900	0.945	0.982	0.830	0.944	0.943	0.945	0.790	0.904	0.910	0.942	0.939	0.951	0.746	
F1	0.934	0.787	0.762	0.829	0.820	0.918	0.899	0.974	0.790	0.729	0.710	0.740	0.932	0.783	0.975	0.792	0.946	0.947	0.970		
F2	0.942	0.846	0.969	0.845	0.735	0.599	0.932	0.940	0.934	0.892	0.944	0.868	0.932	0.942	0.948	0.961	0.941	0.979	0.942	0.915	
F3	0.923	0.886	0.813	0.870	0.661	0.965	0.660	0.623	0.764	0.868	0.919	0.730		0.848	0.859	0.879	0.922	0.915			
F4	0.913	0.938	0.725	0.833	-0.905	0.810	0.749	0.823	0.804	0.912	0.922	0.931	0.569	0.842	0.870	0.744	0.923	0.932	0.930		

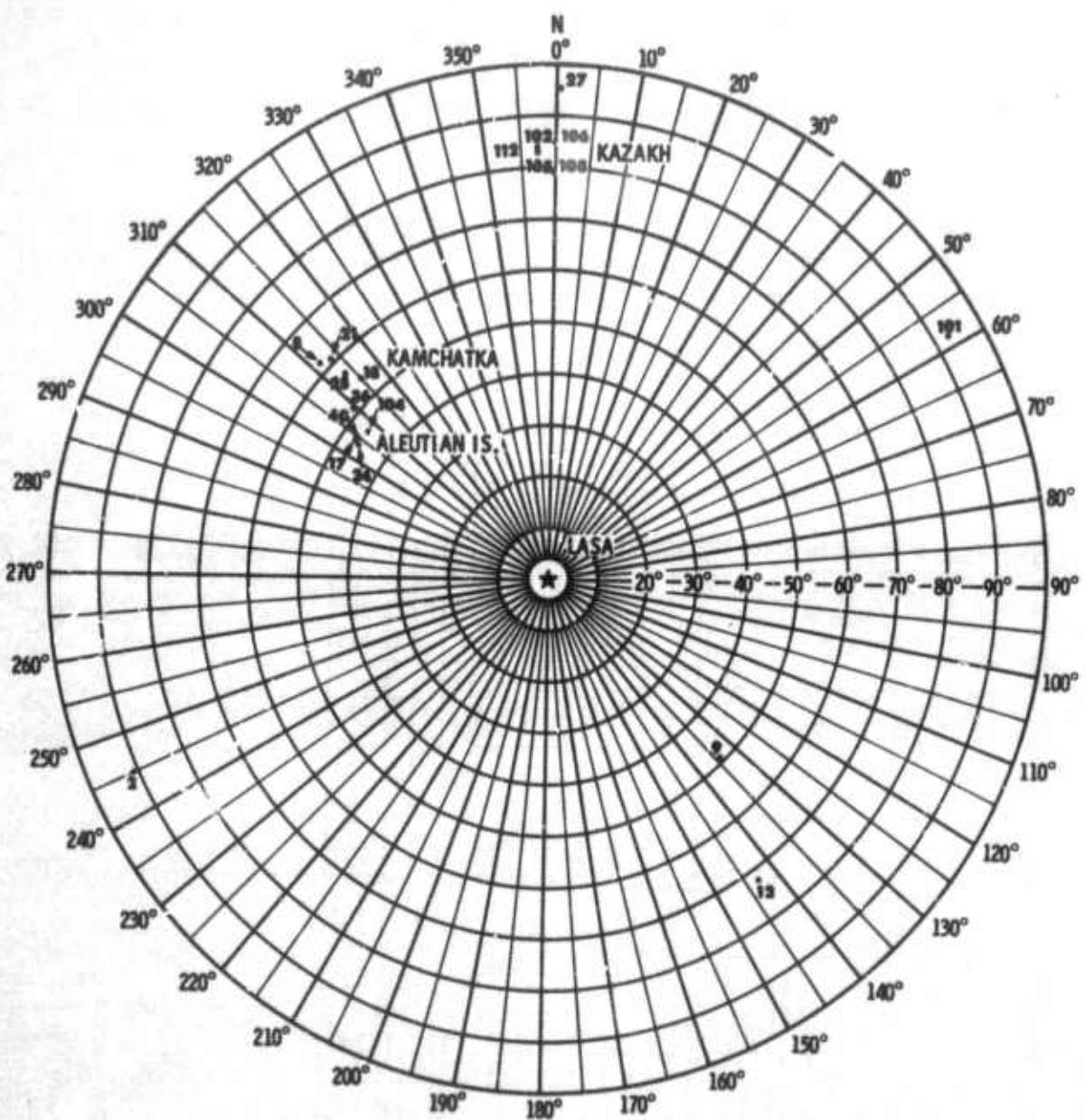


Figure 8. Location of Events Used for Subarray Output Processing



Event 27 (Tadzhik), which had excellent subarray waveform duplication across LASA, is shown in Figure 9.

Table 9 shows some subarrays having very low coefficients for a few events. For example, the coefficients for subarrays B3 and D1 (and, to a lesser extent, A0 and F4) were low for all five nuclear explosions from Kazakh.

Figure 10 shows event 105; the signal waveform was significantly different on these subarrays.

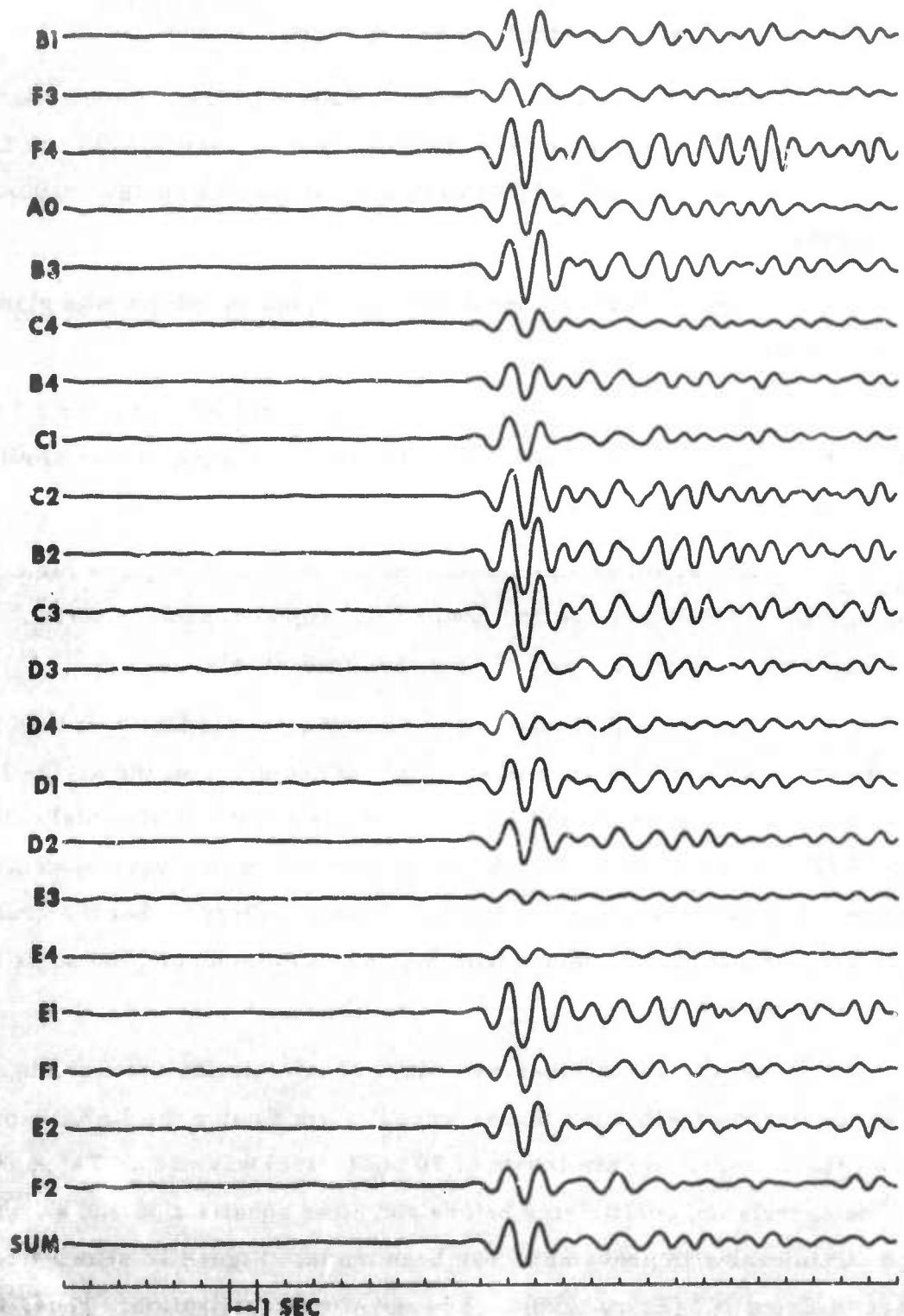
Figure 11 compares the D1 output and LASA sum for all five events. While D1 was consistently different from the sum, it was similar for each event.

Among other anomalous outputs were E3 (very low for event 2, Fiji), and D3 and E2 (very low for Event 101, Algerian nuclear blast). Note that these subarrays were "normal" for the other events.

The anomalies seemed to depend quite critically on both event azimuth and epicentral distance (i.e., angle of incidence of the arrival). For example, subarrays D2 and E1 were low for event 9 (Colombia) but not event 12 (Peru), which had about the same azimuth but a larger epicentral distance. A possible explanation for this "tuning" effect is that the crustal filtering under a subarray varies with both event azimuth and the angle of incidence of the arrival.

For several subarrays with low correlation coefficients, 11-pt (1-sec) Levinson equalization filters were designed using the LASA sum as the reference trace. A gate length of 70 pts (7 sec) was used. Table 10 lists the correlation coefficients before and after equalization and shows that a considerable improvement has been made. Figure 12 shows 4 subarrays of Event 102 (E. Kazakh) before and after equalization. Thus, it appears that for the few subarrays with anomalously low coefficients, signals can be equalized using short Levinson filters.

SUBARRAY



**Figure 9. Event 27 (Tadzhik) as Recorded
by Subarray Outputs**

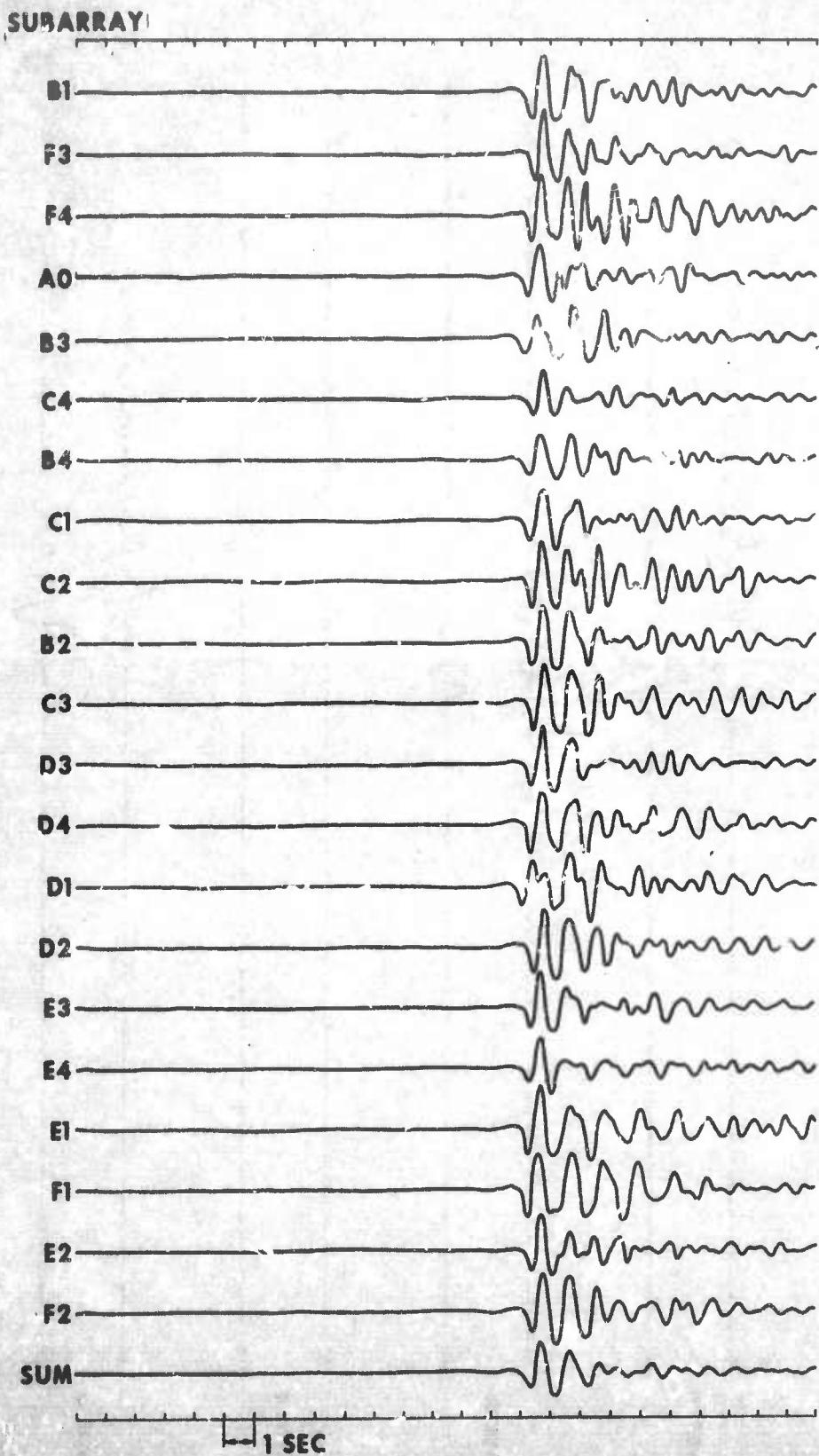


Figure 10. Event 105 (E. Kazakh) as Recorded by Subarray Outputs

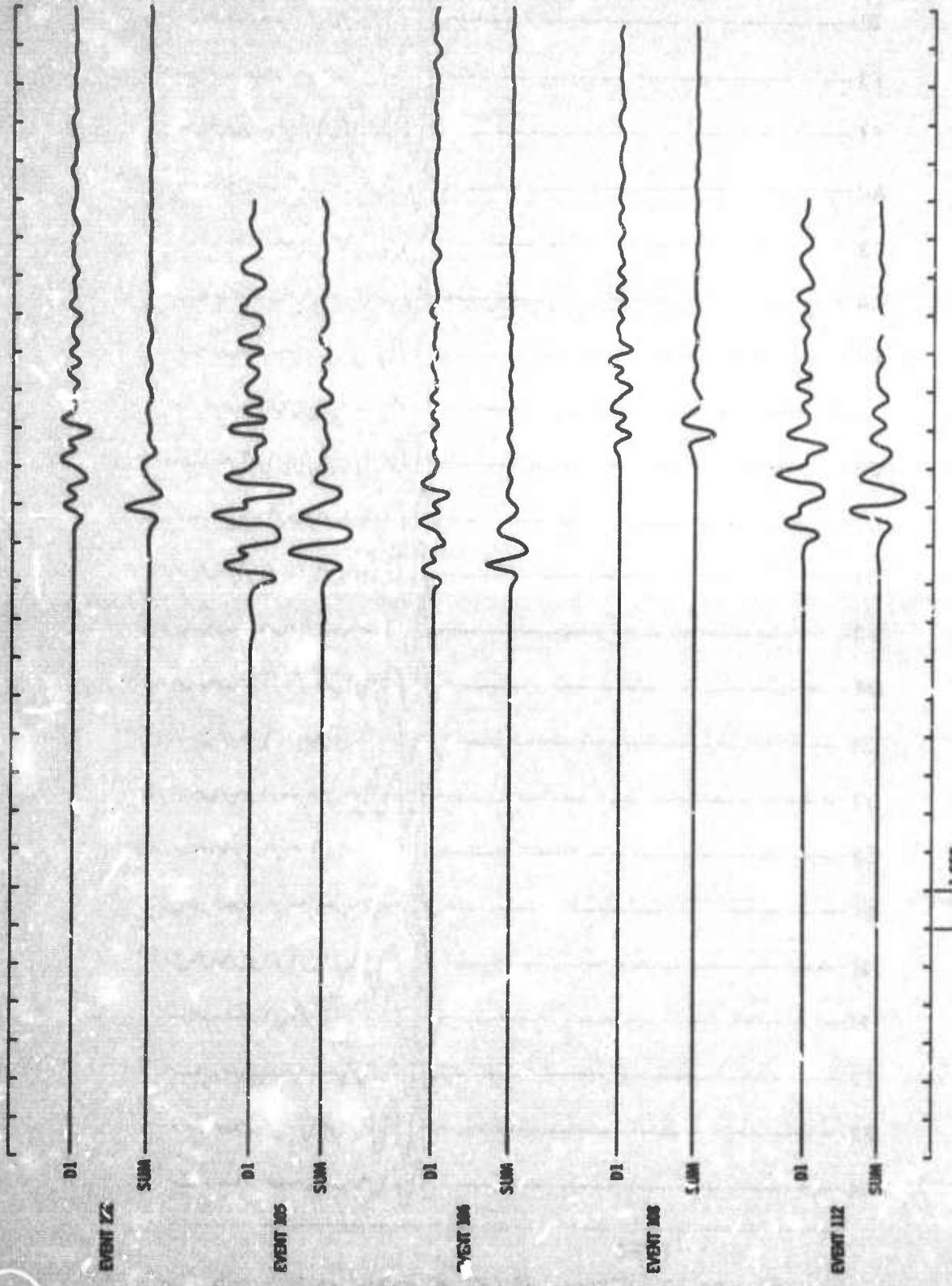


Figure 11. Subarray D1 and Reference Trace for Events
From Kazakhstan Region



Table 10
EFFECT OF LEVINSON EQUALIZATION ON CORRELATION COEFFICIENTS

Event	Gate Length	Subarray	Correlation Coefficient	
			Before Equalization	After Equalization
101	16 points	D3	0. 477	0. 774
		E2	0. 570	0. 761
102	20 points	F4	0. 744	0. 913
		A0	0. 713	0. 940
9		B3	0. 487	0. 856
	32 points	D1	0. 406	0. 806
2		D2	0. 481	0. 711
	28 points	E1	0. 209	0. 647
		E3	0. 142	0. 684

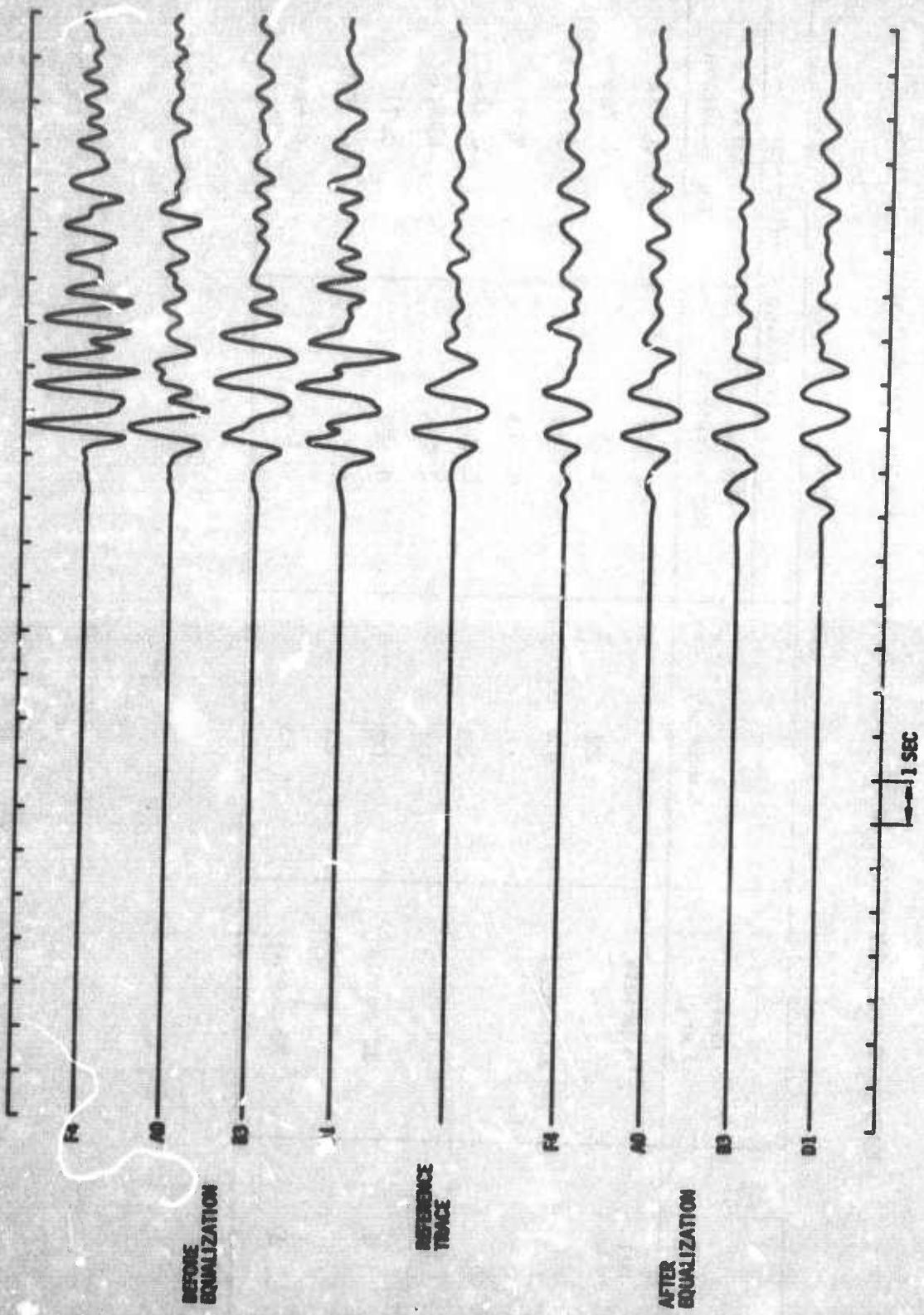


Figure 12. Event 105 (G. Kazakh), Four Subarrays Before and After Equalization



Amplitude variations of subarray outputs were generally quite large (Table 11). Thus, amplitude equalization for all events was necessary (and, except for the few subarrays with anomalously low coefficients, probably sufficient). As expected, the subarrays having the largest and smallest amplitudes varied with different events.

Table 12 lists the correlation coefficient means and variances, the signal degradation, and the signal-to-noise ratios for the LASA sum. Figure 13 is a plot of average coefficient versus signal-to-noise ratio. No significant trend is observed, indicating that the signals used were large enough to prevent the ambient noise from influencing the correlation coefficients.

Figure 14 is a plot of average coefficient versus signal degradation. The trend observed previously is not evident here, which is rather surprising because the two measurements are roughly equivalent. No explanation can be offered for this discrepancy; however, the signal degradation across LASA was small (less than 2 db for all events).

As stated in Section III-A, because of the excellent waveform similarity within subarrays, correlation-coefficient values for single seismometers between subarrays are similar to those for subarray outputs. Table 13 compares the two sets of coefficients for the two events common to both studies. The same gates were used to compute both sets. It can be seen that good agreement exists — both low and high values correspond.



Table 11

MAXIMUM AMPLITUDE VARIATION ACROSS ARRAY

Event	Maximum Amp Variation (db)	Maximum Subarray	Minimum Subarray
2	17.1	C2	E3
101	23.1	F2	D3
12	18.5	F2	D2
9	17.6	E3	A0
24	14.1	D1	B3
17	12.2	D1	B3
40	11.1	D1	E4
104	5.6	C4	F1
36	12.7	B2	B3
18	15.0	C3	F1
25	16.0	C3	F1
21	17.5	C3	E1
8	14.3	D4	E1
105	5.1	F3	B3
108	19.3	C2	B3
112	7.6	F4	C4
102	16.7	F4	D1
106	14.3	F4	B4
27	14.0	B2	E3
29	21.2	F4	E4
Average	14.5		

Table 12

RESULTS FOR SUBARRAY-OUTPUT PROCESSING

Event:	Gate Length (Points)	Correlation Coefficients		Signal Degradation (db)	S/N on Reference Trace
		Average	Variance		
2	28	0.917	0.0306	0.41	409
8	20	0.913	0.0049	0.45	239
9	32	0.785	0.0276	0.18	673
12	34	0.859	0.0042	1.17	76
17	32	0.883	0.0053	0.94	1207
18	36	0.846	0.0129	0.27	129
21	31	0.879	0.0076	1.61	94
24	18	0.873	0.0070	0.31	201
25	28	0.919	0.0075	1.92	107
27	30	0.958	0.0006	0.07	235
29	28	0.881	0.0143	0.50	148
36	15	0.915	0.0027	2.00	62
40	29	0.879	0.0037	0.76	52
101	16	0.843	0.0145	0.91	246
102	22	0.828	0.0200	1.12	546
104	28	0.941	0.0007	1.18	1113
105	30	0.809	0.0131	2.02	1567
106	20	0.845	0.0217	1.51	584
108	16	0.834	0.0306	1.50	226
112	22	0.838	0.0134	0.82	1833

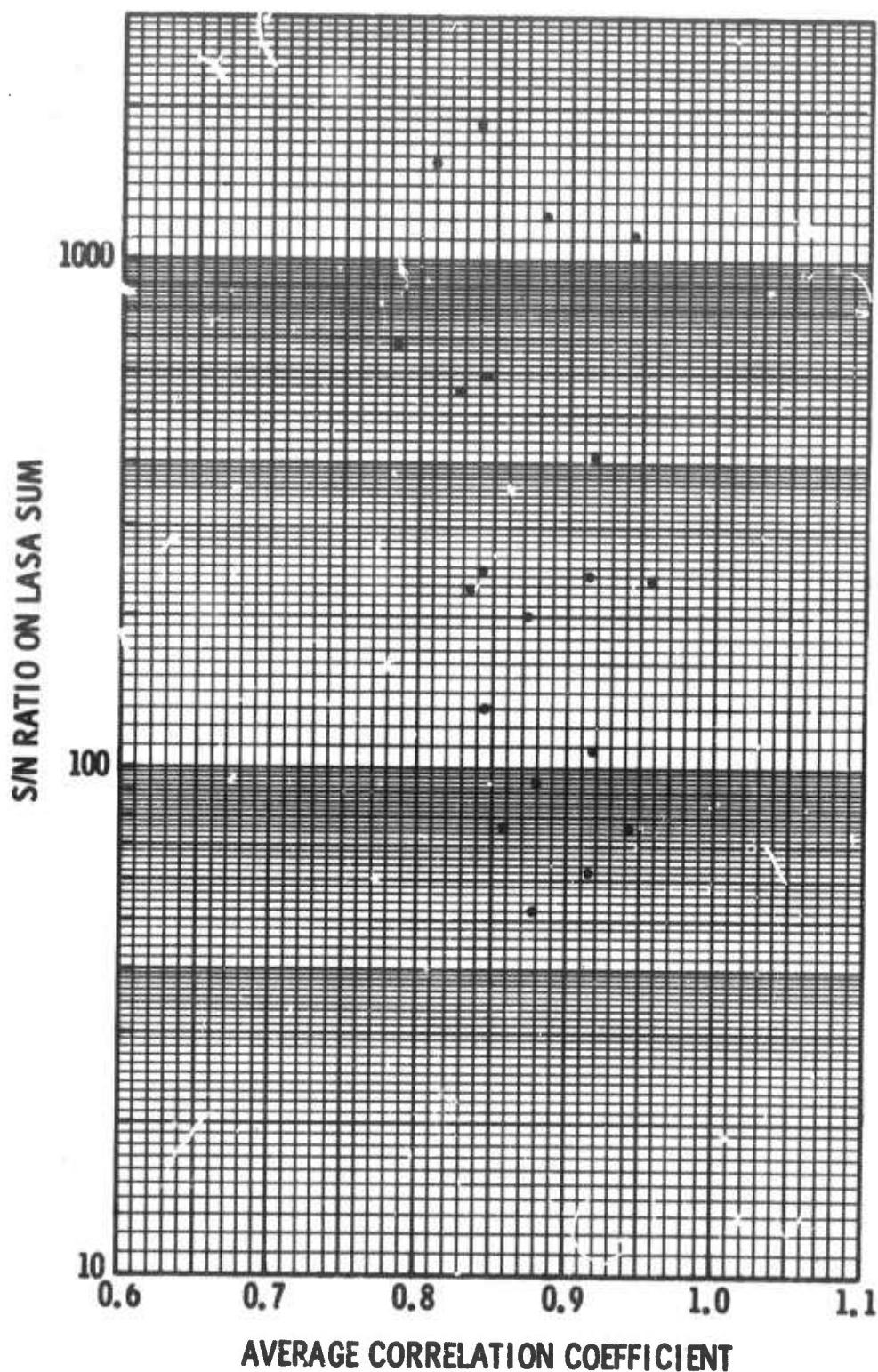


Figure 13. Average Correlation Coefficient
Versus Signal-to-Noise Ratios On
The LASA Sums for Events Used
for Subarray Output Processing

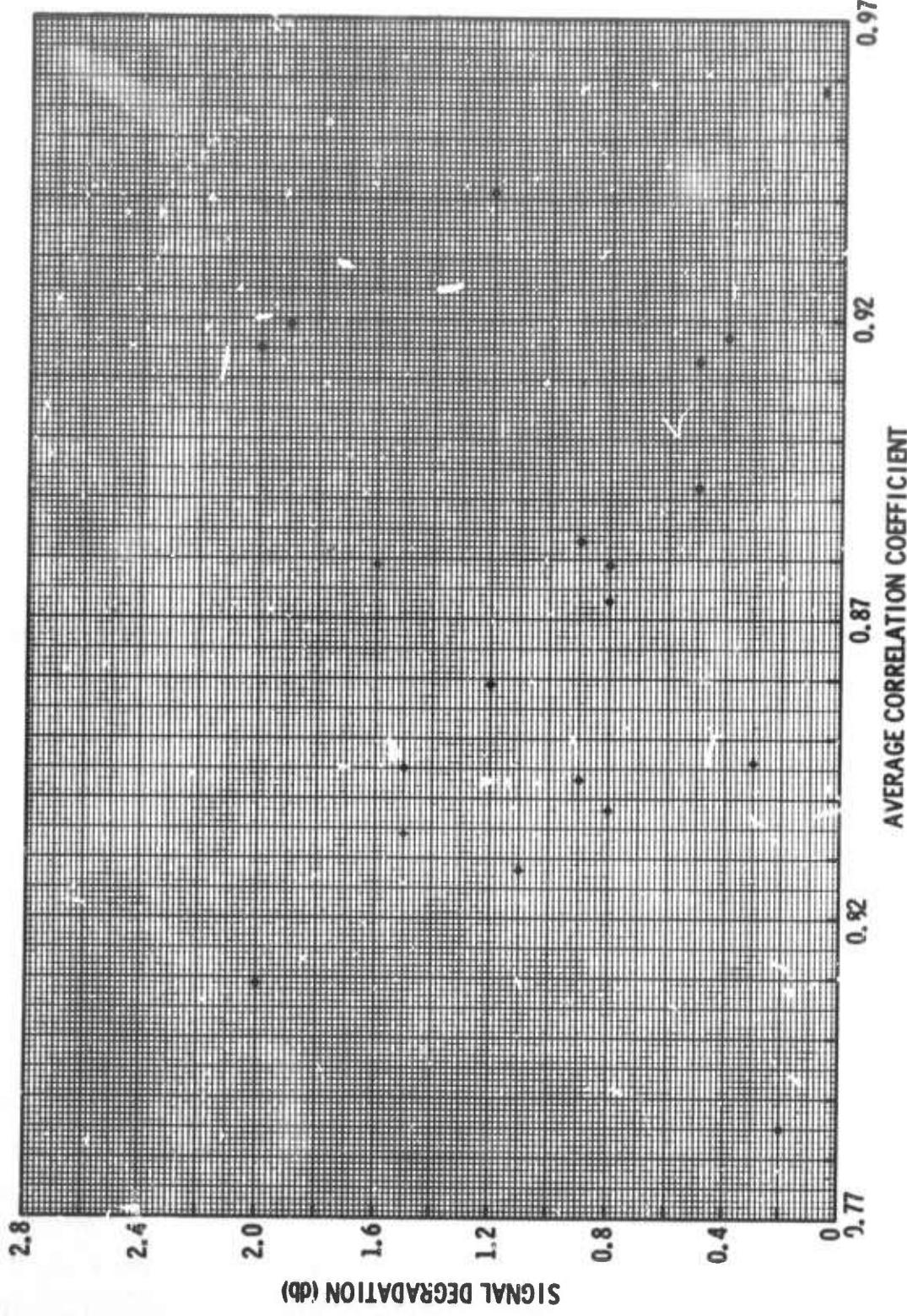


Figure 14. Average Correlation Coefficient Versus Signal Degradation for Events Used for Subarray Output Processing



Table 13

**COMPARISON OF THE CORRELATION COEFFICIENTS
BETWEEN SUBARRAY OUTPUTS AND SINGLE-SEISMOMETER OUTPUTS**

Subarray	Colombia		Andreanof Islands	
	Single Seismometers	Subarray Outputs	Seismometers	Subarray Outputs
B1	0.855	0.849	0.975	0.988
F3	0.783	0.878	0.657	0.661
F4	0.786	0.833	0.866	0.905
A0	0.798	0.764	0.851	0.824
B3	0.877	0.904	0.861	0.918
C4	0.811	0.825	0.892	0.926
B4	0.964	0.925	0.848	0.897
C1	0.936	0.912	0.979	0.93
C2	0.939	0.885	0.938	0.900
B2	0.828	0.804	0.900	0.914
C3	0.875	0.837	0.957	0.936
D3	C.862	0.876	0.883	0.887
D4	0.760	0.722	0.825	0.845
D1	0.844	0.837	0.953	0.953
D2	0.338	0.481	0.757	0.903
E3	0.875	0.908	0.793	0.703
E4	0.760	0.695	0.789	0.838
E1	0.421	0.209	0.923	0.881
F1	0.756	0.629	0.825	0.820
E2	0.878	0.827	0.949	0.977
F2	0.941	0.785	0.775	0.735
Mean	0.804	0.785	0.806	0.873



SECTION IV

CONCLUSIONS

This study showed that

- Within subarrays, waveform duplication was excellent. Variations in amplitude were sufficiently large to require amplitude equalization prior to multichannel processing, but no more sophisticated equalization technique was necessary.
- Between subarrays, waveform duplication was generally very good. Again, amplitude equalization was required and, for most purposes, was probably sufficient.
- A few subarrays had significantly different waveforms for some events. The event location appeared to determine which subarrays exhibited this anomalous behavior. A possible explanation for this effect is that crustal filtering beneath a subarray varies with event location. Short Levinson filters appeared to equalize the anomalous waveforms adequately.
- Scattered energy does not appear to be a problem at the LASA site.
- Because of the excellent intrasubarray-signal similarity, the similarity for single seismometers between subarrays was approximately the same as that for subarray outputs.

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing entries must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

Texas Instruments Inc.
Science Services Division
P. O. Box 5621, Dallas, Texas

2. REPORT SECURITY CLASSIFICATION

Unclassified

2A GROUP

3. REPORT TITLE

Short-Period Signal Waveform Similarity at LASA

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Special

5. AUTHOR(S) (Last name, first name, initial)

Laney, Thomas D.; Harley, Terence W.

6. REPORT DATE

August 1, 1967

7A. TOTAL NO. OF PAGES

43

7B. NO. OF REFS

1

8A. CONTRACT OR GRANT NO.

AF33(657)-16678

8B. ORIGINATOR'S REPORT NUMBER(S)

A. PROJECT NO.

VT/6707

9B. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

c.

d.

10. AVAILABILITY/LIMITATION NOTICES This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Chief, AFTAC.

11. SUPPLEMENTARY NOTES

ARPA Order No. 599

12. SPONSORING MILITARY ACTIVITY

Air Force Technical Applications Center
VELA Seismological Center
Headquarters USAF, Washington, D. C.

13. ABSTRACT

Similarity of signal waveform across the Large Aperture Seismic Array (LASA) was studied. The analysis technique depended on differences in waveform shape but not on amplitude differences. The waveform was found to be very similar both within subarrays and, except for a few cases, between subarrays. Thus, 1-pt (amplitude) equalizations usually is sufficient when processing LASA data both on the subarray and large-array levels.

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Large Aperture Seismic Array Short Period Waveform Similarity: of Seismometers within a Subarray. of Seismometers between Subarrays. of Subarray Outputs.						

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